Total Ionizing Dose Effects on Voltage-to-Frequency Converters*

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ABSTRACT

Three different voltage-to-frequency converters were tested to determine how ionizing radiation affected their critical specifications. All three were fabricated with bipolar technologies. A popular charge-balancing architecture converter, AD652, was most sensitive with low dose rate (LDR) due to its tight specifications. The other astable-multivibrator architecture converters, AD537 and AD654, performed much better at high dose rate and low dose rate.

I. INTRODUCTION

A voltage-to-frequency converter converts analog voltages to certain frequency square waves. In a VFC, the output continuously tracks the input analog signal; in other words, the output frequency responds directly to changes in the input signal and external clock synchronization is not required for operation. These V/F converters are used in high resolution analog-to-digital converters and high precision integrators in analog circuit applications. One application in a deep space mission is in a circuit for acceleration-to-frequency conversion. The circuit uses a micro-electromechanical system (MEMS) accelerometer with a V/F converter to provide a variable frequency output. A microprocessor is then programmed to measure the frequency and compute the applied acceleration of the spacecraft.

Most work on total dose degradation of linear devices has concentrated on operational amplifiers and comparators. Work on analog-to-digital converters [1-4] has shown that total dose effects in those devices cannot be interpreted as simple extensions of op-amps or comparators because they use a different architecture and are also affected by the stability of internal references. This paper discusses total dose effects on voltage-to-frequency converters which impose different requirements on internal circuitry, and are also very high-precision devices (for example, linearity is typically specified between 0.002 and 0.05%).

Three different devices were included in the study. All three are bipolar linear devices which are potentially sensitive to dose-rate effects. One of the main goal of the work was to evaluate low dose-rate effects and to determine which parameters were most affected at both high and low dose rates.

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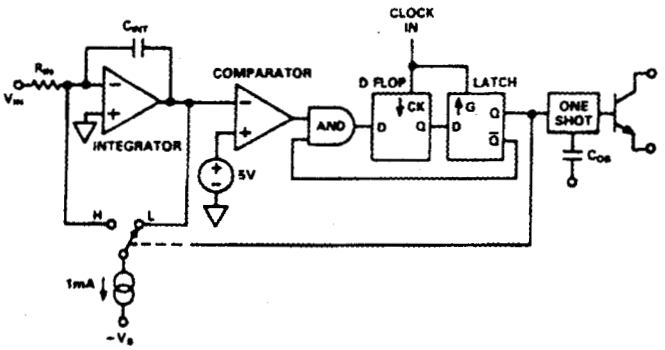

Figure 1. Simplified block diagram of the charge-balance converter architecture of the AD652 [5].

II. DEVICE DESCRIPTIONS

There are two types of architectures used to implement the voltage-to-frequency function, charge balancing and astable multivibrator types. The output of the charge balance type converter is a train of pulses of constant width and height, resulting in a very low duty cycle for small analog voltage inputs. The duty cycle increases with increasing input voltage. The astable multivibrator architecture is a basic current-to-frequency converter and its output is a square wave [5]. Thus, the two architectures provide very different output formats.

AD652 is a synchronous charge-balance VFC which is typically used in designs for precision analog-to-digital conversion. This converter is similar to other VFCs in that an integrator is used to perform a charge balance of the input signal with an internal reference current. It performs with a typical nonlinearity of 0.002 % up to 2 MHz output frequency, a very

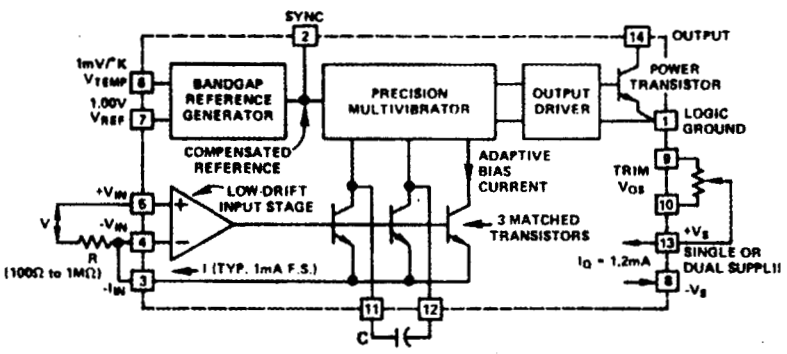

Figure 2. Simplified block diagram of the astable-multivibrator architecture AD537 [5]; the AD654 is similar

demanding level of accuracy. This converter uses a charge balancing technique for conversions as shown in Figure 1. The AD652 uses an external clock to define the full-scale output frequency, rather than depending on the stability of an external capacitor. It also has an internal 5V reference for use in precision applications. Usually it is used to offset the noninverting comparator input in the voltage-to-frequency mode.

The other type of architecture, the astable multivibrator (current-to-frequency converter), is used on the AD654 and AD537 and it is shown in Figure 2. These converters use a current controlled precision multivibrator as the primary timing element. The input op-amp converts the analog input voltage into a proportional unipolar current which drives the precision multivibrator and timing capacitor through the three matched transistors. This current then determines the charging and discharging rate of the timing capacitor which determines the output frequency of the converter. They provide about an order of magnitude less accuracy than charge-balance converter.

The AD537 also has an internal precision voltage reference, linearity error is 0.05 % for 10 kHz full scale input, and requires a single supply. AD654 requires a minimum number of external components and linearity error is 0.03% for 250 kHz full scale. AD654 converter can operate with a full-scale frequency up to 500 kHz and can be use with both single and dual power supplies.

A summary of the features of the three converters is shown in Table 1 below.

Table 1. Features of the three converters

Device	Architecture	Typical Linearity	Internal Reference	Max. Total Supply Voltage
AD537	Astable Multivibrator	0.05%	Yes	36V
AD652	Charge Balance	0.002%	Yes	36V
AD654	Astable Mutivibrator	0.03%	No	36V

III. Test Results

A. Experimental Approach

Devices were irradiated with a cobalt-60 room type irradiator at room temperature using a lead-aluminum shield to remove low energy scattered radiation. Devices were irradiated at two conditions to determine sensitivity to dose rate effects. One set was irradiated at 25-50 rad(Si)/s and the other at 0.005 rad(Si)/s. All devices were statically biased with a mid-scale voltage applied to inputs. An Analog Devices LTS-2020 test system was used for electrical characterization tests.

B. Linearity

The AD652 converter is fabricated with a conventional bipolar process using lateral and substrate pnp transistors. This device exhibited large differences in parametric degradation at low dose rate, particularly voltage-to-frequency linearity which showed much more degradation at a mid-scale voltage rather than end-point input voltages. The maximum specification limit is 0.02%, therefore, it exceeded the specification limit at about 8 krad(Si) as shown in Figure 3. This parameter did not exceed the specification limit up to the final HDR level of 50 krad(Si).

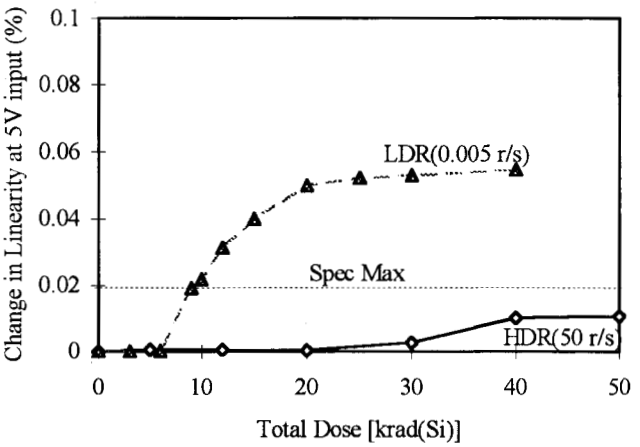

Figure 3. Linearity degradation of the AD652 V/F converter at two dose rates.

The two converters with a different architecture, AD537 and AD654, showed small changes in linearity at LDR up to 18 krad(Si) as shown in Figure 4. AD537 showed a sharp increase in linearity at 24 krad(Si) and decreased to the final total dose level of 32 krad(Si). However, the maximum specified limit is 0.25 %, therefore, the linearity is still well within specification limit. AD654 showed slight decrease in degradation at 32 krad(Si). These converters showed insignificant degradation in linearity and linearity errors were within the specification limits with HDR up to 50 krad(Si).

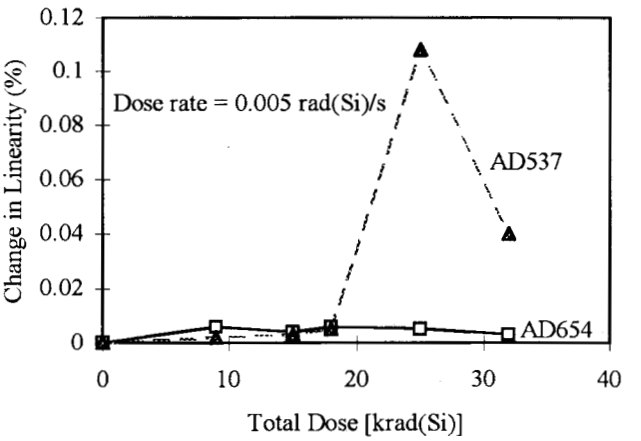

Figure 4. Linearity degradation with LDR [0.005 rad(Si)/s] for AD537 and AD654.

Full scale error is the calibration error of the converter circuit to produce the desired output frequency with a full scale input applied. This is an important parameter for converter linearity. It degraded severely with LDR for AD654 and it is shown in Figure 5. It exceeded the specification limit at 10 krad(Si) with LDR. However, it was within specification with the final dose level 20 krad(Si) HDR. In contrast, the AD537 showed insignificant degradation up to the final dose level of 32 krad(Si) with both HDR and LDR.

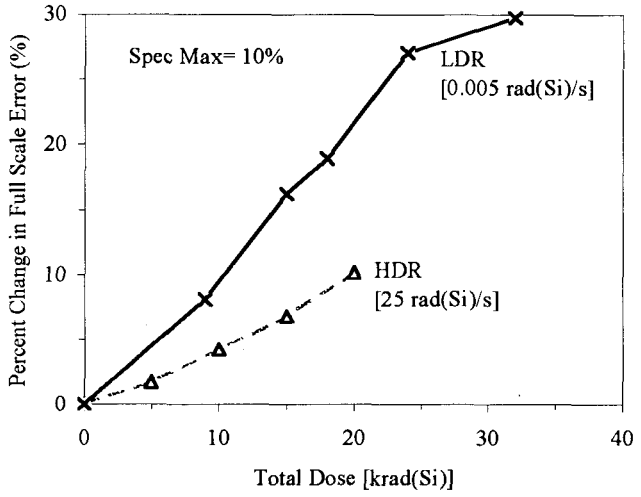

Figure 5. Full scale error degradation of the AD654 at two different dose rates.

C. Reference Stability

The on-chip 5V voltage reference of the AD652 showed extremely large voltage changes (this part is supposed to have typically 0.002 % precision), even at high dose rate. At low dose rate changes in the internal reference voltage are more than 5 times greater than at high dose rate as shown in Figure 6. The extremely large change in reference voltage would have a serious effect on total dose degradation. Therefore, the internal reference should not be used.

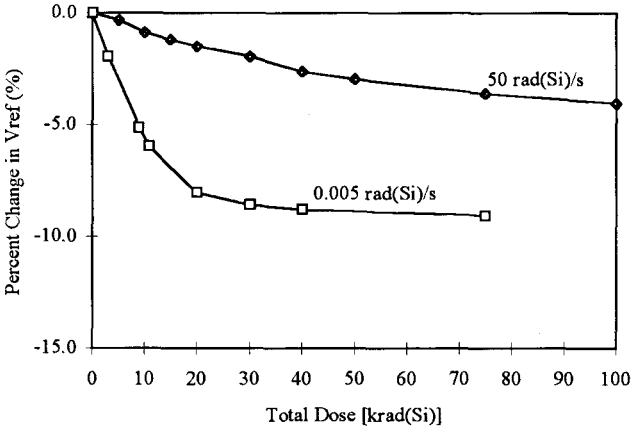

Figure 6. Comparison of the AD652 internal 5V reference voltage degradation at HDR and LDR.

The reference voltage for the AD537 showed much less degradation, about 8 mV at 32 krad(Si). The maximum specified change in reference voltage is only 5% of 1 V. However, there was a definitely large difference in degradation with HDR and LDR. The changes were about 0.8 % for LDR and 0.1 % for HDR as shown in Figure 7. The voltage reference for the AD654 was not included in measurements because it is not specified in the manufacturer's data sheets.

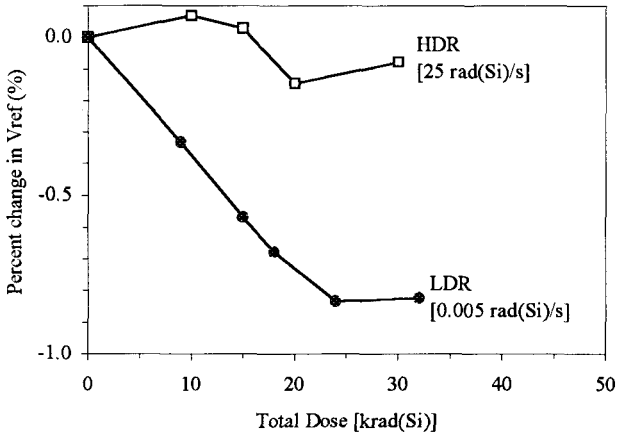

Figure 7. Reference voltage degradations of AD537 at two different dose rates.

D. Amplifier Characteristics

Input bias currents (Iib) for the astable-multivibrator architecture converters, AD654 and AD537, showed large degradation at LDR and it is plotted in Figure 8. The input bias current showed small degradation with HDR for both devices. The maximum specification limit of input bias current for the AD654 is 50 nA. This parameter exceeded the specification limit at about 7 krad(Si), a low total dose failure level and it continue to increase up to the total dose level of 24 krad(Si).

Input bias current degradation of the AD537 is less severe. The maximum Iib specification limit for AD537 is 100 nA and it exceeded the limit at about 18 krad(Si), three times higher level than the AD654 converter. Both devices showed decreases of the input bias current in between 24-32 krad(Si).

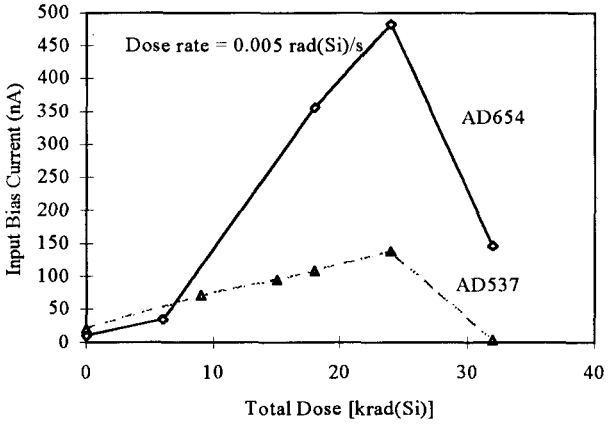

Figure 8. Input bias current degradations of AD537 and AD654 at LDR of 0.005 rad(Si)/s.

Input offset voltages (Vos) for AD537 showed very small degradation up to 30 krad(Si) with HDR as shown in Figure 9. It showed insignificant change until 24 krad(Si) and then increased sharply at 32 krad(Si) LDR to about 2.8 mV which is still within the maximum specification limit of 5 mV.

The AD654 was only irradiated to 20 krad(Si) with HDR and showed insignificant degradation up to the final dose level. However, LDR testing was carried to the final dose level of 32 krad(Si). The maximum specification limit for the input offset voltage is 1 mV. Thus, it exceeded the specification limit at about 26 krad(Si).

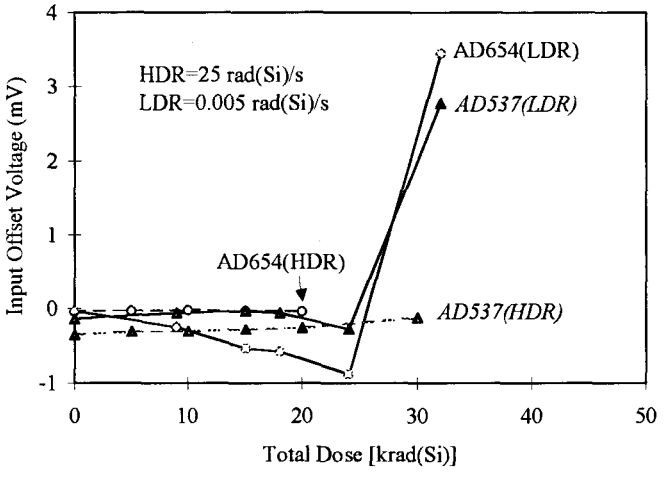

Figure 9. Input offset voltage degradations of AD537 and AD654 at two different dose rates.

E. Output Drive

Output interfaces for AD537 and AD654 are open collector outputs. The output sink current in logic zero is an important parameter for many circuit applications. The output current degradation of AD537 is shown in Figure 10 with both HDR and LDR. The minimum specification limit is 20 mA for AD537. The output current degradation of AD654 was very small, less than 1 mA and it was well within specification limit of 10 mA minimum.

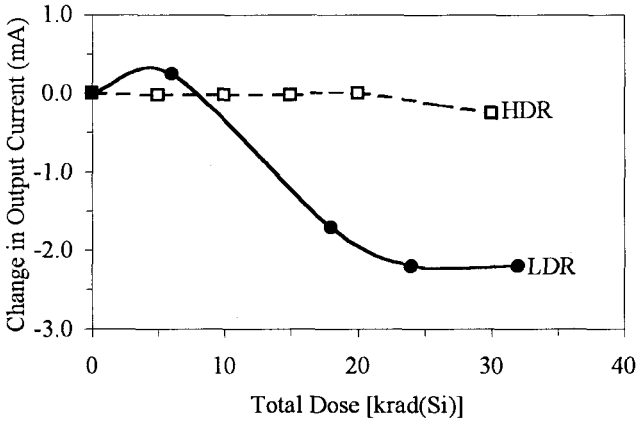

Figure 10. Change in output current degradation of AD537 at two different dose rates.

Power supply current for both converters, AD537 and AD654 showed insignificant degradation with LDR and HDR up to the final total dose level of 32 krad(Si). Supply current for AD537 degraded about 2.8% and 2% for AD654.

IV. Summary

The charge-balance converter, AD652, was strongly affected by dose rate, especially with the critical parameters such as linearity and reference voltage. The other astable-multivibrator architecture converters, AD537 and AD654, were not nearly dose rate sensitive. Some parameters showed slightly larger degradation with LDR. However, most parameters were within the specification limits. These are promising results for these converter to be used in space systems applications.

References

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